Numerical Weather Prediction

A historical study of extreme rainfall events in the 20th Century

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A historical study of extreme rainfall events in the 20th Century

By W. H. Hand

Abstract

Extreme rainfall events by their very nature are rare but common enough to require consideration of the possibility and associated serious flood risk by DEFRA (Department for Environment, Food and Rural Affairs). It is therefore vital that signals of the likelihood of such events occurring in any given region be recognised as early as possible, preferably 24 hours or more in advance. The primary aim of this study was to examine events in the 20th century in order to ascertain any common hydrological and meteorological features that could be used operationally to provide early recognition of the possibility of an extreme rainfall event that could lead to serious flooding.

1. Background

This report describes the Met Office contribution to a joint study of extreme hydro-meteorological events carried out in collaboration with the University of Salford on behalf of the Department of the Environment, Food and Rural Affairs (DEFRA) in 2001/2002. The aim of the research was to investigate the nature of very extreme rainfall events, particularly the meteorological situations leading to their occurrence, and the susceptibility of river catchments to their spatial and temporal rainfall patterns. It is expected that the results of the investigations will eventually contribute to improved short range forecasts of the probability of extreme rainfall and associated flood risk.

2. Selection and classification of events

Rainfall events that give rise to serious flooding involve four main ingredients. They are intensity and duration of precipitation, the wetness of the ground and the response of the rainfall catchment. The key items considered in this study were the first two, which are the meteorological ones. Hydrological contributions and other factors were noted when applicable.

Criteria for event selection were established by making use of the rainfalls estimated in the Flood Studies Report Volume II (FSR) as the "maximum" falls possible for durations less than 1 hour, and the one in one hundred year return period for durations greater than one hour. Values are shown in table 1 below.

Average Annual Rainfall (AAR) mm	Duration (hours)						
	0.25	0.5	1	24	48	72	96
	Maximum fall possible			Amount for 1:100 year return period			
500 – 1400	47	65	83	100	123	135	150
1400 – 2800	**45**	**62**	**79**	**152**	**193**	**219**	**247**
> 2800	43	59	75	228	309	356	410

Table 1. *Maximum falls possible for durations less than one hour and the one in one hundred year return period for durations greater than one hour as a function of average annual rainfall (AAR). Note that the amounts for greater than one hour correspond to the top of the AAR range.*

Since most "extreme" rainfalls occur over lowland Britain, it was decided to use the middle range of AAR in Table 1 as a definition of the lower limit of extreme rainfalls. It is useful to compare this classification with the "classification of heavy falls in short periods" by E.G. Bilham published in British Rainfall 1935. Bilham put falls into three categories - "noteworthy", "remarkable" and "very rare" as shown in Table 2.

Time (mins)	Noteworthy	Remarkable	Very rare
5 or less	10.9	17.3	26.8
10 or less	13.8	21.6	33.2
20 or less	17.3	26.8	40.9
30 or less	19.7	30.3	46.2
60 or less	24.5	37.6	56.8
90 or less	27.8	42.4	64.0
120 or less	30.4	46.2	69.4

Table 2. *Lower limits of rainfall amount as a function of duration for three categories of event according to Bilham 1935. (Note that the original article has a duration resolution of ten minutes).*

Comparing Tables 1 and 2 it can be seen that the lower limit chosen for extreme events is substantially greater than that for the "very rare" category in the Bilham classification.

Event selection was done by searching through a database of "notable rainfall events in the 20th century" held in the Met Office and picking out those that exceeded a curve of values derived from the criteria shown in bold type in Table 1 (see Figure 4). Other sources of information such as the FSR and the British Rainfall series of publications were also utilised to generate the list of extreme events in Table 3.

Date	Location	Total	Duration	Basic type	Reference
12/07/00	Ilkley	95	1.25	Convective	Met.Mag. August 1900 British Rainfall
12/07/01	Maidenhead	92	1	Convective	British Rainfall
21/10/08	Portland (Dorset)	175	5	Frontal***	British Rainfall
09/06/10	Reading	130	2	Convective	British Rainfall
26/08/12	Norwich	186	22	Frontal	British Rainfall
25-26/09/15	Inverness	201	40	Frontal	British Rainfall
16/06/17	Kensington	118	2.3	Convective	Met.Mag. July 1917
28/06/17	Bruton (Somerset)	243	8	Frontal***	British Rainfall
29/05/20	Louth (Lincolnshire)	119	3	Convective	British Rainfall
19/08/24	Brymore (Somerset)	225	5	Convective***	British Rainfall
19-22/07/30	N. Yorks	250	60	Frontal	British Rainfall
08/08/31	Boston (Lincs)	155	11	Frontal***	British Rainfall
02-03/11/31	W. Britain	240	48	Orographic	Met.Mag. Jan 1932 British Rainfall
11/07/32	Cranwell (Lincs)	126	2	Convective	British Rainfall
26/09/33	Fleet (Hampshire)	131	4	Convective	British Rainfall
22/07/34	West Wickham (Kent)	116	1.66	Convective	British Rainfall
25/06/35	Swainswick (Bath)	150	2.75	Convective***	British Rainfall
15/07/37	Boston (Lincs)	139	12	Frontal***	British Rainfall
04/08/38	Torquay	127	2.25	Convective***	Met.Mag. Sept 1938 British Rainfall
16/07/47	Wisley (Surrey)	102	1.25	Convective	British Rainfall
12/08/48	SE Scotland, Tweed	160	12	Frontal	Met.Mag. Jan 1949
15/08/52	Lynmouth	228	12	Frontal***	Met.Mag. Dec 1952

					British Rainfall
26/06/53	Eskdalemuir	80	0.5	Convective	Met. Mag. Nov 1953
17-18/12/54	Loch Quoich	254	22.5	Orographic	British Rainfall. DWR.
18/07/55	Martinstown (Dorset)	280	15	Frontal***	British Rainfall
11/06/56	Bradford	165	2	Convective***	British Rainfall
08/06/57	Camelford (Cornwall)	138	2.5	Convective	Met.Mag. Vol. 86 1957 pp 339-343
05/08/57	Rodsley (Derbyshire)	152	8.5	Convective	British Rainfall
05/09/58	Knockholt (Kent)	131	2.5	Convective	Met.Mag. Oct 1960 British Rainfall
11/07/59	Hindolveston (Norfolk)	93	0.3	Convective	
07/10/60	Horncastle (Lincs)	178	3	Convective***	
06/06/63	Southery (Ouse)	150	3	Convective	
18/07/64	Bolton	56	0.25	Convective	
17/12/66	Glen Etive	199	18	Orographic	
08/08/67	Dunsop Valley (Lancs)	117	1.5	Convective	
10/07/68	Chew Stoke (Bristol)	175	9	Frontal***	
15/09/68	Whitstable (Kent)	190	20	Frontal***	Met. Mag. 1974 V103.255-268, 288-300.
31/10/68	Tollymore Park (Co.Down)	159	24	Frontal	
11/06/70	Pershore	67	0.4	Convective	
27/06/70	Wisbech	51	0.2	Convective	
01/08/73	Norwich	138	4	Convective	
20/09/73	West Stourmouth (Kent)	191	24	Frontal	
09/11/73	Blaneau Ffestiniog	147	15	Orographic	
17/01/74	Loch Sloy	238	30	Orographic	
14/08/75	Hampstead	171	3	Convective	Met. Mag. June 1981
25/06/80	Sevenoaks	116	1.75	Convective	Met. Mag. V109 1980 pp 362-363
01/08/80	Orra Beg (Antrim)	97	0.75	Convective	
05/08/81	Tarporley (Cheshire)	132	5	Convective	
19/05/89	Walshaw Dean (Halifax)	193	2	Convective	Weather. Vol 46 7;1991
31/08/94	Bungay (East Anglia)	146	12	Frontal	

Table 3. *List of extreme event dates showing date, location, rainfall amount (mm) and duration (h), classification and published source of additional information. In the classifications, frontal*** indicates a significant convective component and convective*** indicates significant frontal forcing.*

3. Data sources used for analysis of events

Up to 1960 the British Rainfall series of annual publications was invaluable for providing detailed rainfall information for each event and also on most occasions a brief description (sometimes with maps) of the meteorological conditions and associated flooding. Some events were also published in the Meteorological Magazine (Met. Mag.) and referenced by British Rainfall. Descriptions of events were often from interested members of the public who gave valuable insights into the possible nature of the system responsible for the event. Two examples are as follows; *" Sir, - On Thursday afternoon, July 12th, a terrific thunderstorm raged over a part of the West Riding of Yorkshire, beginning in the west about noon, and extending or propagating itself gradually eastwards. The direction of the thunder clouds was from S to N, although as is usual in such cases, the surface winds were very variable under the storm area, and in the district to the eastward the sky was very clear and blue, and a strong easterly wind blew into towards the storm centre ... "* That was part of a description of the Ilkley storm in 1900 published in Met. Mag.. More recently we have the following extract - *"At Hedgebarton, 15 miles to the northwest of Torquay, Mr W.K. Kitson noted that the rain did not begin until 4h 15m and by 8h as much as 5.86 inches was recorded. Very large hailstones occurred but the hail was of short duration. For four hours the lightning appeared to be continuous. It appeared to be a purely local storm confined to an area a mile in diameter and*

other localities appear to have had purely local storms. " which was part of an account of the storm of 4/8/38 in British Rainfall.

After 1960 the British Rainfall series changed style and was much less useful for this study and additional information had to be gleaned from the Met Office Daily Weather Report (DWR) series and published articles. It is perhaps ironic that the early events were better recorded in detail but the underlying meteorological information was less good than in more recent years.

Upper air data were only available from the 1920s and radar and satellite data from the 1950s. Moreover it was only in the 1930s that fronts were routinely analysed on charts published in the DWR so for the early events these had to be professionally inferred from available data.

Flooding information was also well documented and easy to determine in British Rainfall prior to 1960 but less so after that date.

4. Basic analysis of events

Out of the 50 cases, (coincidentally a round number), there were 30 deemed to be predominantly convective, 15 predominantly frontal and 5 orographic types. Although in many cases orography was a contributing factor due to forced ascent of moist air, the cases deemed to be orographic were where general orographic uplift was the dominant mechanism for the very high rainfall. The distributions of events throughout the 20th Century are shown in Figures 1 and 2.

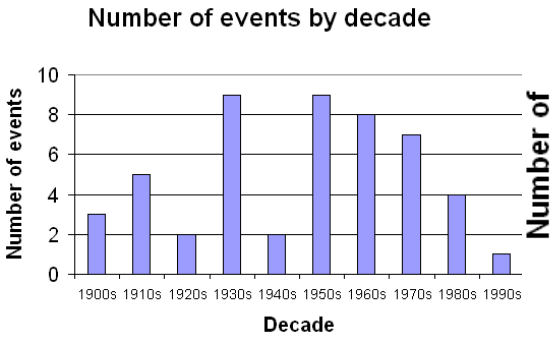

Figure 1. *Number of extreme events per decade.*

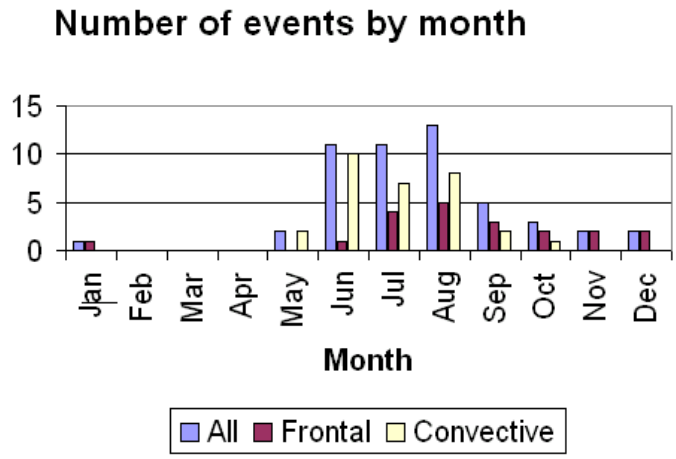

Figure 2. *Number of extreme events per month and type (frontal type includes orographic)*

The distribution per decade (Figure 1) indicates no significant variation during the century with the 1930s and 1950s having most cases and more cases in the second half of the 20th century than in the first. However, no conclusions should be drawn from this since the first half included two world wars and a less extensive network of professionally maintained rainfall gauges.

The monthly distribution (Figure 2) is more interesting. There were no events in February, March or April. Most events occurred during the summer months with a rapid increase in number in June with a gradual tailing off during the autumn. Naturally convective events tail off more quickly than frontal ones with no convective

events in November, December or January since insolation is an important forcing factor for convection. An explanation for this highly skewed distribution of extreme events is that relatively low sea temperatures and colder air during the Spring would mean less available moisture for rain producing systems. Even though atmospheric instability can be high in April, these results would suggest that although shower events can be sharp at that time of year, they are not capable *by themselves* of providing extreme rainfalls. It is also interesting to compare the minimum temperature distribution of a typical inland location like Manchester Airport (Figure 3) with the monthly extreme event distribution. The 1961-1990 monthly minimum temperature distribution is similarly skewed with higher values in the autumn compared to the spring months as a consequence of higher soil and sea temperatures.

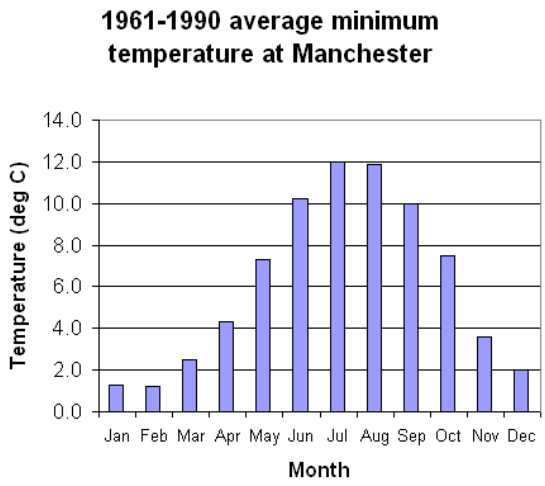

Figure 3. *Monthly distribution of minimum temperature at Manchester*

Going through the cases it soon became obvious that a number of the frontal cases had a significant convective element. This was usually characterised by embedded thunderstorms shown plotted within a general band of otherwise frontal dynamical precipitation, for example, Lynmouth 1952.

Similarly some convective events arose due to instability being released due to the presence of an otherwise inactive front, for example, Bradford, 1956. These cases are labelled with *** in Table 3.

The basic classifications in Table 3 are shown in graphical form as a function of rainfall amount and duration in Figure 4.

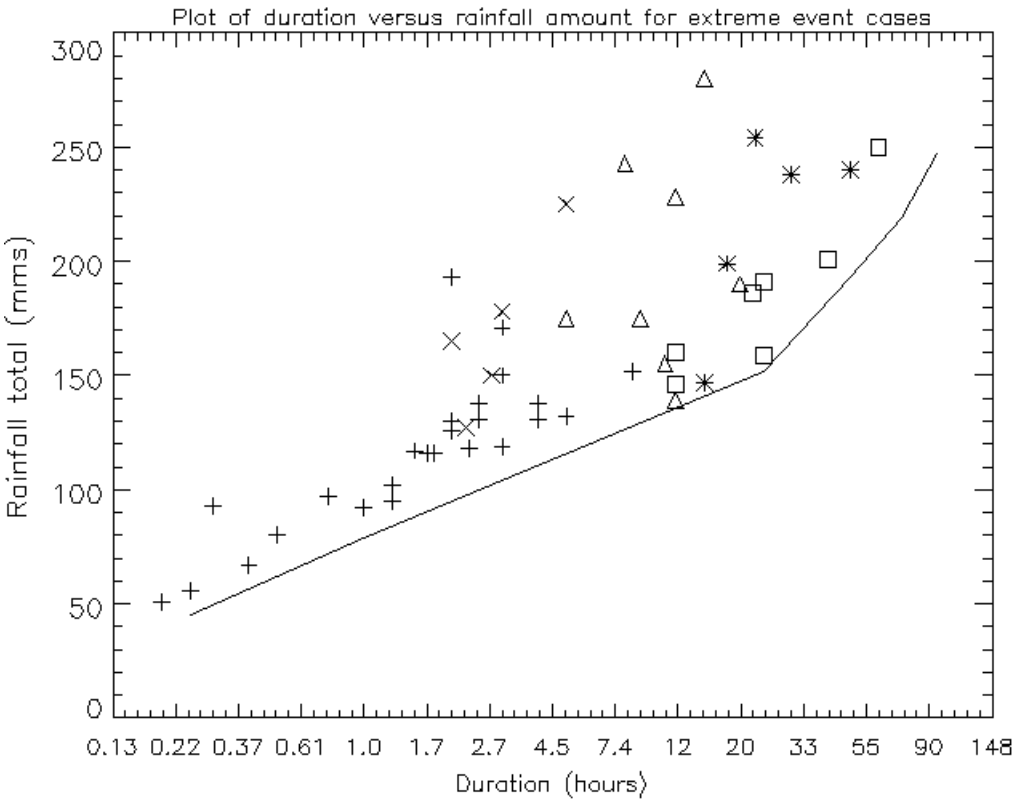

Figure 4. *Plot of rainfall amount (mm) versus duration (h) (on a logarithmic scale) for each of the five event categories listed in table 3. '+' = convective , 'X' = convective*** (frontal forcing), * = orographic, Δ = frontal*** (with embedded instability) and 'square' = frontal. The solid line plot indicates the lowest threshold used for extreme event classification as in table 1.*

This graph is interesting in that the convective cases seem to be closely scattered about a well-defined line. The scatter increases for durations greater than about 2 hours when convective cases with dynamical forcing become included. The frontal events are also grouped so as to increase linearly but with more scatter than the convective cases with some notable outliers. The largest rainfall amounts for specific durations occurred in cases where there was significant embedded instability, for example, Bruton 1917, Lynmouth 1952 and Martinstown 1955.

As well as meteorological features some hydrological aspects were examined using the comprehensive and detailed information in the British Rainfall series up to 1960 and in the 1968 edition. Out of the 34 cases up to and including 7/10/60 and the 1968 cases, 94% of the rainfalls caused flooding. A lot of the flooding was serious and damaging, and in some cases tragic, as at Louth in 1920 and Lynmouth in 1952. In the two non-flooding cases (11/7/32, 26/9/33) there was no mention of widespread flooding though it would be surprising if local flooding did not occur given the intensity of the rainfall on those occasions. Deluges of water cascading quickly down hillsides, for example at Ilkley in 1900 caused several serious events. A major factor in the Lynmouth and Louth floods was build up of water behind debris, which subsequently burst to give catastrophic results. Looking at the rainfall events in the two months prior to each extreme case, an estimate was made of the wetness of the ground. 34% of the cases in the sample were estimated to have very wet ground beforehand, undoubtedly contributing to flooding. (In the two non-flooding cases the ground was not wet prior to the event). This analysis implies that all extreme rainfall events are highly likely to give some sort of flooding problems, which will be exacerbated if the

rainfall falls in sensitive catchments, over steep orography or over already very wet ground.

5. Analysis of frontal and orographic cases

5.1 Orographic events

There were 5 cases in the sample; 2-3/11/31, 17-18/12/54, 17/12/66, 9/11/73 and 17/1/74. Note that all of these events were in the months November, December and January. All cases involved a long sea fetch (greater than 2000 Km) in a strong west to southwest straight airflow with a high pressure region centred either over the Bay of Biscay (12/54, 12/66, 11/73, 01/74) or Greece with a ridge to Spain (11/31) as summarised in Table 4.

Event	Amount (mm)	Duration (h)	Fetch direction	Fetch distance (km)	600m wind speed (m/s)	Source dewpoint (deg C)
2-3/11/31	240	48	SW	2500	25	17
17-18/12/54	254	23	WSW	3000	25	14
17/12/66	199	18	WSW	3500	25	18
9/11/73	147	15	WSW	2000	15	16
17/01/74	238	30	WSW	4000	25	15

Table 4. *List of orographic events giving rainfall amount and duration, the fetch of the airmass specifying direction and distance, estimated mean wind speed along fetch at 600m (from surface isobars) and the estimated airmass source dewpoint.*

The key parameters from the sample would seem to be fetch (direction and distance), wind speed and a moist and warm tropical maritime airmass.

An example of a typical synoptic situation that could lead to extreme orographic rainfall is shown in Figure 5 for 17/12/66. The high rainfall occurred over western Scotland in the strong to gale force warm sector west-southwesterlies behind the warm front. Note the long fetch of warm and moist air which has air temperatures in the source region around 21 deg C.

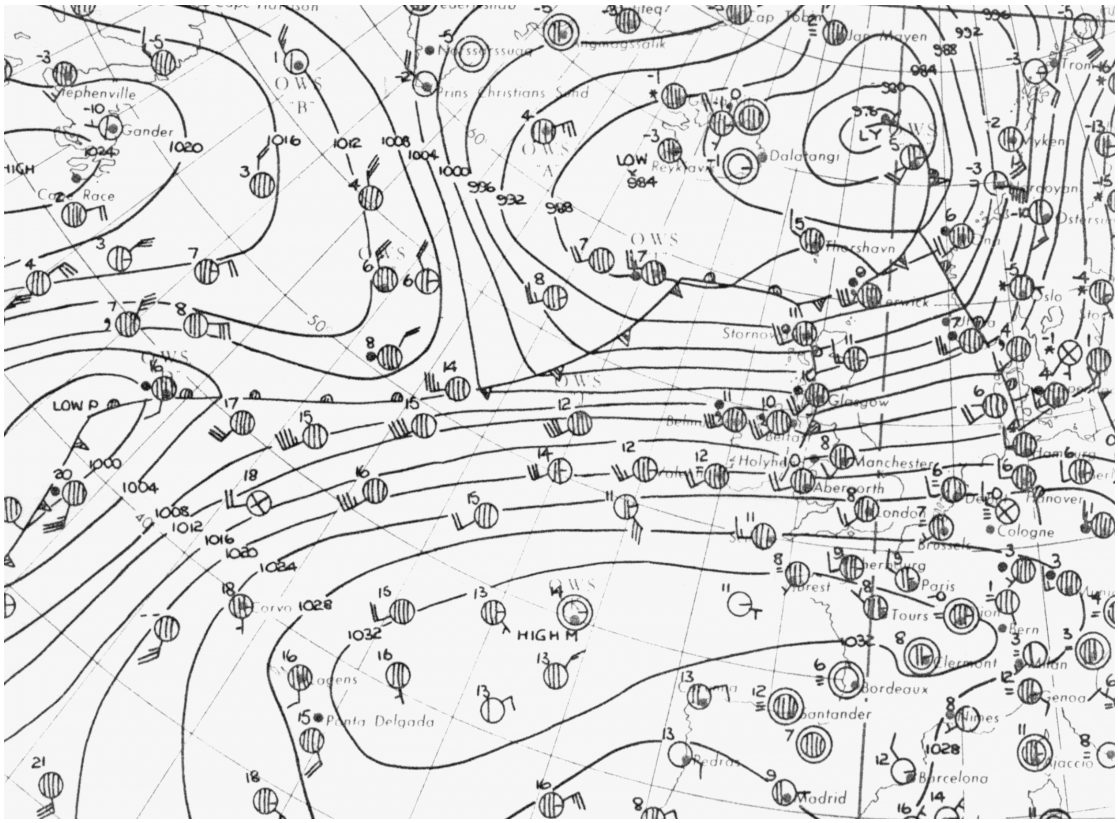

Figure 5. *Surface chart for 1200 GMT 17/12/66 (from DWR).*

5.2 Frontal events

Looking at the surface synoptic charts for all of the 15 frontal cases (excluding orographic ones) it quickly became obvious that all of the events were either associated with a slow moving frontal system or a depression that was close by, and in 10 cases a combination of both.

Figure 6 shows the aspect of each frontal event in relation to the depression centre. For example a square on the arm labelled 'W' at '-200' would mean that the event occurred 200 Km to the west of the depression.

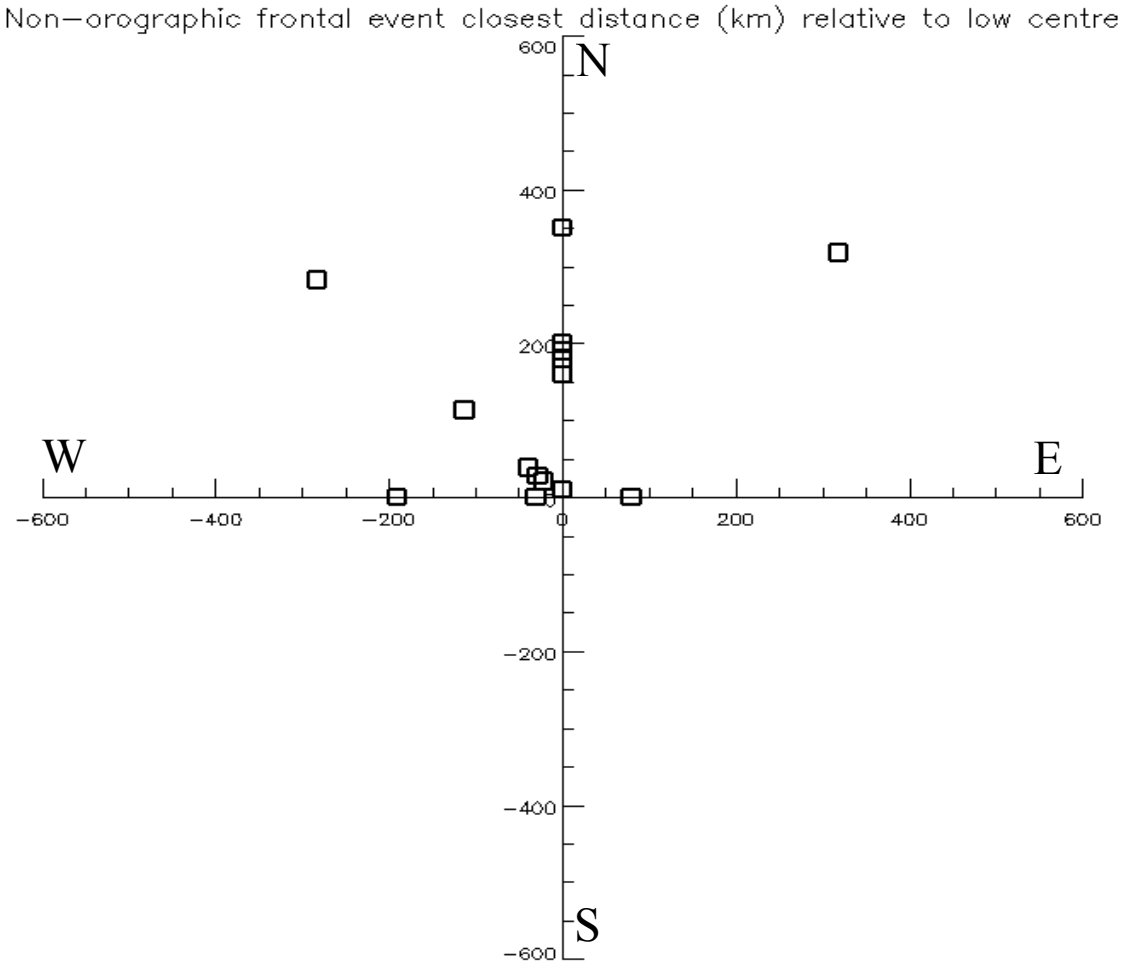

Figure 6. *Direction and closest distance of each frontal event from closest approach of depression centre (0 on the compass cross). (See text for more details).*

None of the 15 frontal events were greater than 450 Km at their closest point from a depression and 75% (12/15) were within 200 Km. In terms of aspect, all events occurred north of a depression and 73% either northwest (NW) or north (N). 60% (9/15) were both NW or N and within 200 Km at closest distance from the low pressure centre. Of those 60%, 6 out of 8 had significant embedded instability (frontal*** category) and 3 out of 7 had little evidence of instability. In 12 out of the 15 cases the speed of the low was less than or equal to 10 m/s and in 7 out of the 15 cases it was less than or equal to 5 m/s.

In 75% (12/15) of cases a slow moving frontal system was involved in the situation. It is interesting to note that the frontal event (Martinstown, 1955) that gave the most rainfall (280 mm in 15 hours) was an almost stationary front extending almost due west to east across southern England with embedded instability.

Since most of the fronts were either to the east or south of the event the rain producing system naturally involved the northward or westward advection and ascent of very moist and relatively warm air. A very good example of this is illustrated in the January 1949 Met. Mag. Article of the 12/8/48 "Tweed floods" and also in Figure 7.

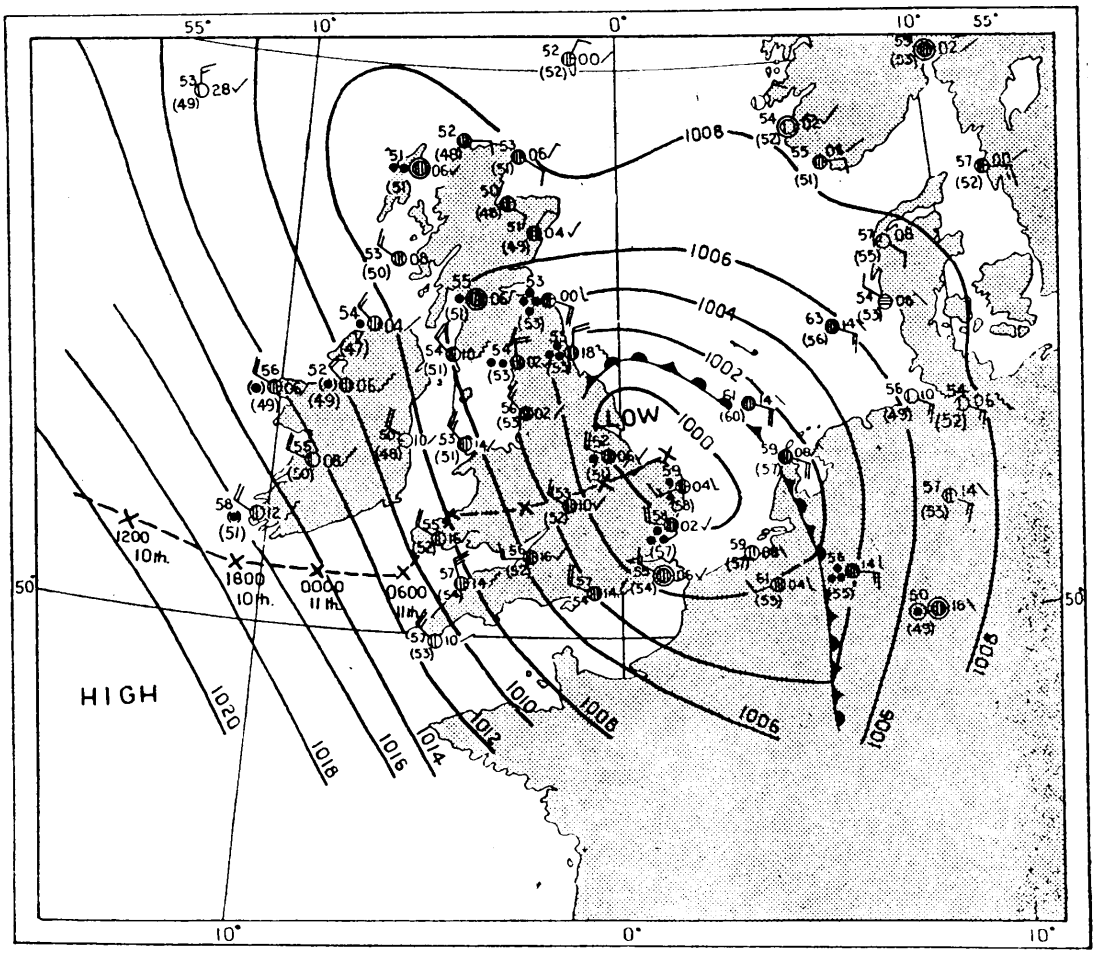

Figure 7. *Surface chart showing movement of depression and associated frontal system and position of low centre at 0600 UTC 12/8/48. (Reproduced from Glasspoole in Met. Mag. 1949).*

The low pressure centre is clearly seen tracking to the south of the Tweed across England with a slow moving warm occlusion to the north providing the prolonged and heavy rainfall.

A fairly similar example on 21/7/30 is shown in Figure 8.

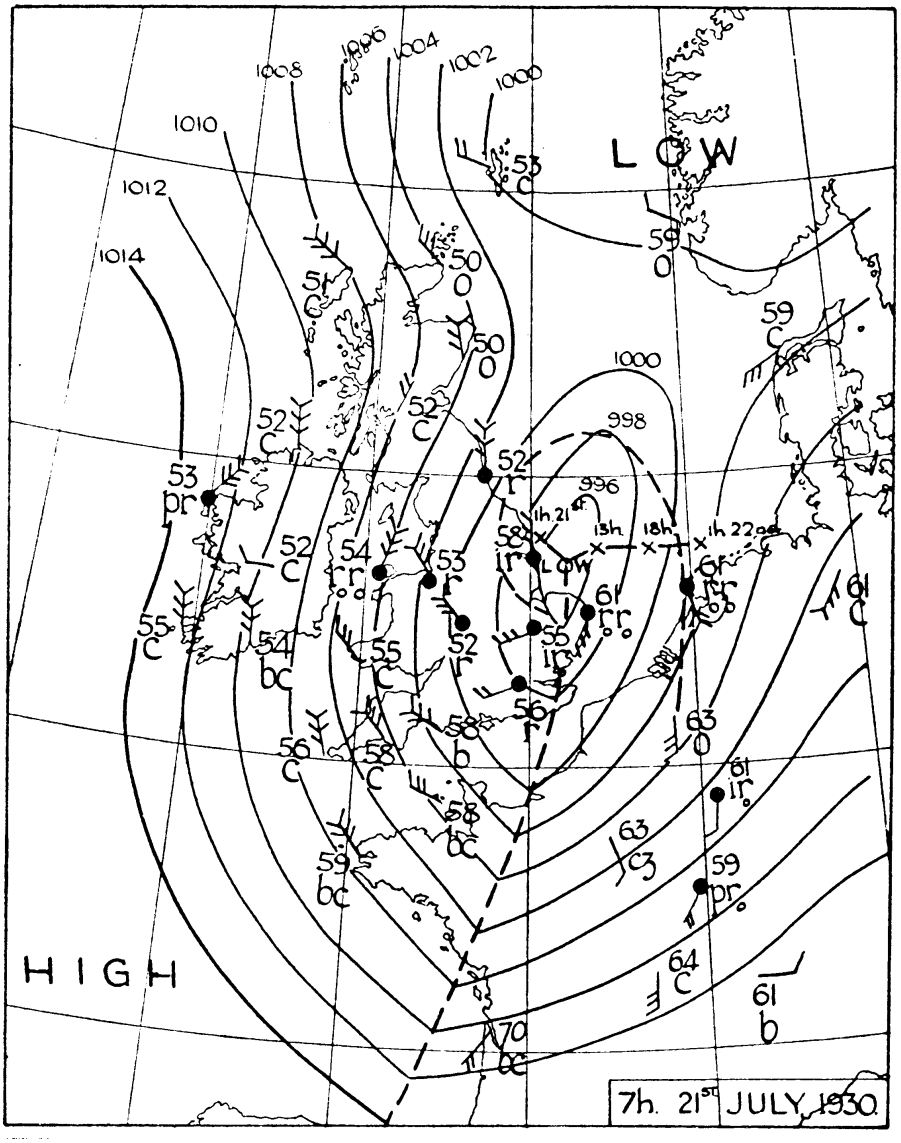

Figure 8. *Surface chart for 0700 UTC 21/7/30. The movement and position of the low at other times is indicated by crosses and the position of fronts by dashed lines. The number of wind feathers indicate Beaufort force. (Reproduced from British Rainfall).*

The rainfall event in north Yorkshire was to the west of the low which moved very slowly east during 21st to 22nd July. The dashed line indicating a front curving round the north and west of the low was probably a slow moving warm occlusion similar to the 1948 case.

The chart for the Lynmouth flood event is shown in Figure 9.

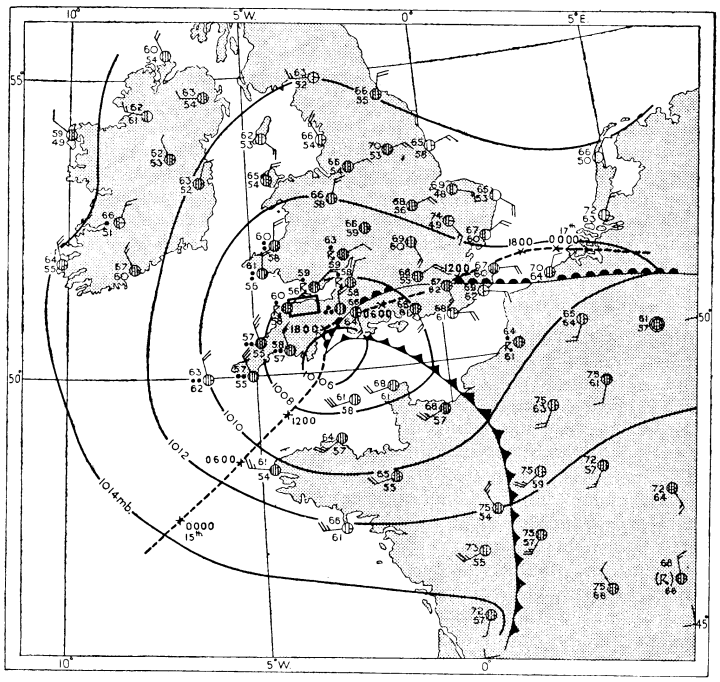

Figure 9. *Synoptic chart for 1500 UTC 15/8/52. (Reproduced from Bleasdale and Douglas in Met. Mag. 1952).*

This again shows a slow moving depression running close and to the southeast of the extreme event. A key feature is the advection of very moist air (indicated by the warm front) northwestwards into the potentially unstable region over Exmoor lying just to the east of an upper trough.

The final example is for 15/9/68 and is shown in figure 10. Again note the very heavy rainfall to the north and west of a small low pressure centre in association with a well-marked warm occlusion with much embedded instability.

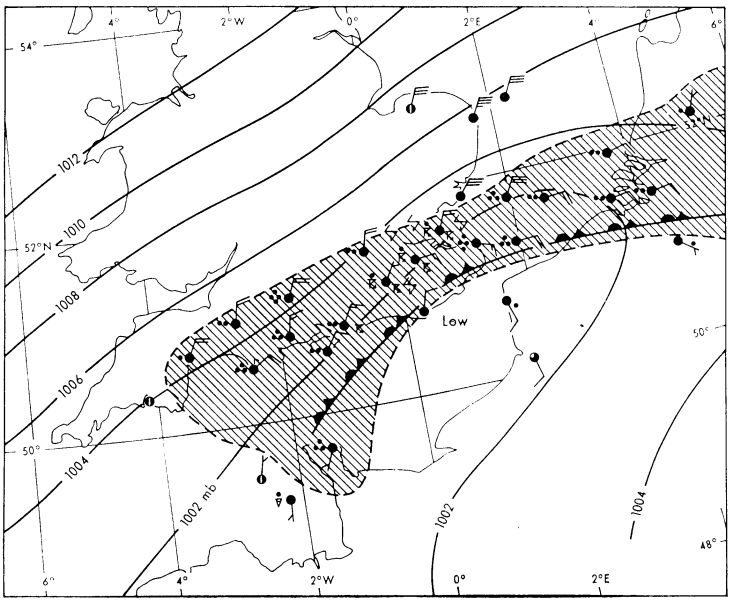

Figure 10. *Synoptic chart for 0900 UTC 15/9/68. (Reproduced from Salter and Richards Met. Mag. 1974).*

6. Analysis of convective cases

The convective cases broadly fell into two categories:

(a) Either where forcing was from a synoptic scale feature such as a front, or updraughts and downdraughts in the system were very strong with a high value of convectively available potential energy (CAPE).

(b) Forcing was either from insolation or a meso-scale feature such as a convergence line or sea breeze and smaller values of CAPE.

Identification of cases where frontal forcing was dominant was straightforward by looking at sequences of plotted observations and reading published accounts. Assessment of CAPE was somewhat laborious with limited upper air information. Therefore, in most cases accounts and observations of large hail were used as a proxy. Hail was reported in a lot of the cases as would be expected in extreme convective events but special mention tended to be made in publications when the hail was large enough to damage crops, greenhouses and other property. These cases were put into category (a). However, in a few cases available data and information were insufficient in order to determine the cause of the convective event. These cases were put into category (b).

The categorization of convective events is shown in Table 5.

	Evidence/cause	Reference
Type (a) events		
09/06/10	Large clusters of rainfall. Large hail.	British Rainfall
16/06/17	Strong vertical wind shear. Large hail.	Met.Mag. July 1917
19/08/24	Trough/cold front ? Substantial hailfall.	British Rainfall
11/07/32	Sea breeze convergence ? Large hail.	British Rainfall
25/06/35	Occlusion. Wind shear. Large hail.	British Rainfall
04/08/38	Occlusion. Wind shear. Large hail.	Met.Mag. Sept.1938
11/06/56	Slow moving frontal zone.	British Rainfall. DWR.
08/06/57	"Unusually heavy hail"	Met.Mag.1957 pp339-343
05/09/58	Large CAPE. "Tennis ball" hail. Tornado.	Met.Mag. Oct. 1960
11/07/59	Trough/small low. Large hail.	DWR.
07/10/60	General thundery rain.	DWR.
06/06/63	Thundery rain. Large hail.	DWR.
14/08/75	Local insolation. Multicell. Large CAPE.	Met.Mag. June 1981
25/06/80	Trough ? Prolonged hailfall.	Met.Mag.1980 pp362-363
19/05/89	Old front in region. Multicell.	Weather Vol 46 7;1991
Type (b) events		
12/07/00	Convergence ? Possible multicell ?	Met. Mag. Aug.1900
12/07/01	Convergence ?	British Rainfall
29/05/20	Trough. Convergence. Line.	British Rainfall
26/09/33	General instability release in easterly.	British Rainfall
22/07/34	Trough ? Squall-like.	British Rainfall
16/07/47	Upper part of split cold front ?	British Rainfall

26/06/53	Convergence. Unstable northerly flow.	British Rainfall. DWR.
05/08/57	Clusters.	British Rainfall
18/07/64	Line. Low pressure over Wales.	DWR.
08/08/67	Orography ?	DWR.
11/06/70	Cluster. Insolation ?	DWR.
27/06/70	Line. Front.	DWR.
01/08/73	Sea breeze ?	DWR.
01/08/80		DWR.
05/08/81	Old fronts.	DWR.

Table 5. Categorization of convective events into type (a) and (b). (See text for details). An indication of the likely cause of the event and other evidence is shown as well as the reference source of the evidence.

Events that contained large hail and events that did not are plotted in Figure 11.

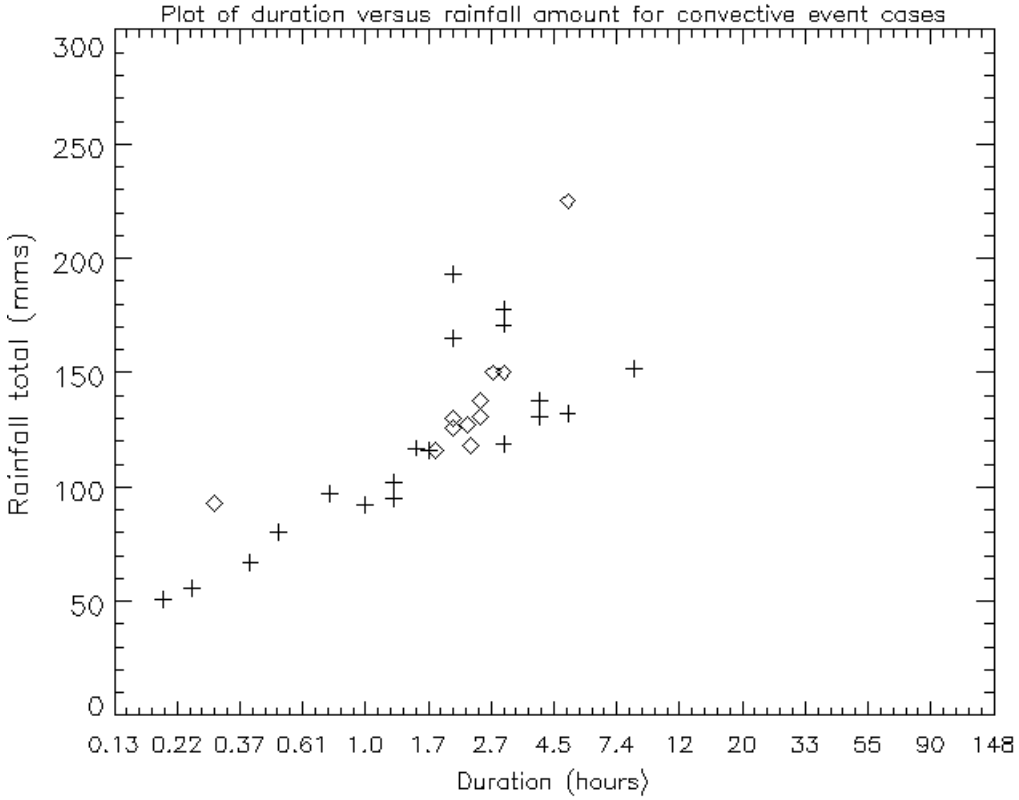

Figure 11. *Plot of rainfall amount (mm) versus duration (h) for the convective event cases. Crosses indicate events where there was no evidence of large hail and diamonds indicate cases where large hail was reported.*

This analysis shows a tight group of cases with large hail with durations in the range 2-3 hours. The non-hail cases in that range are all type (a) cases - 11/6/56, 7/10/60, 14/8/75 (multicell) and 19/5/89 (multicell). There are two outlier large hail events - 11/7/59 and 19/8/24.

This diagram is very encouraging as it implies that if we can identify storms that are likely to have large and damaging hail then we will have some idea of the possible nature of the storm in terms of rainfall duration and amount. Moreover, if storms that

have strong frontal forcing or large CAPE are included then there is a good separation on the diagram (see section 7).

Unlike the frontal and orographic cases it was not possible to identify common synoptic causes. Each case was different in some aspect of detail and an extreme event would not necessarily occur given a similar looking synoptic pattern on another occasion. However, looking in broad terms it was found that out of the 30 convective events, 16 were "weakly forced". Weakly forced means that there was no discernible triggering mechanism on the synoptic scale, however, potential instability could be released by meso-scale features such as troughs, convergence lines, sea breezes, temperature hot-spots, local orography etc. It was also encouraging that only 33% of type (a) cases were weakly forced (those that were, produced multicells or large hail) whereas 73% of type (b) cases were weakly forced.

A good example of a weakly forced situation is provided by the Hampstead storm of 1975 where the general synoptic situation is shown in Figure 12.

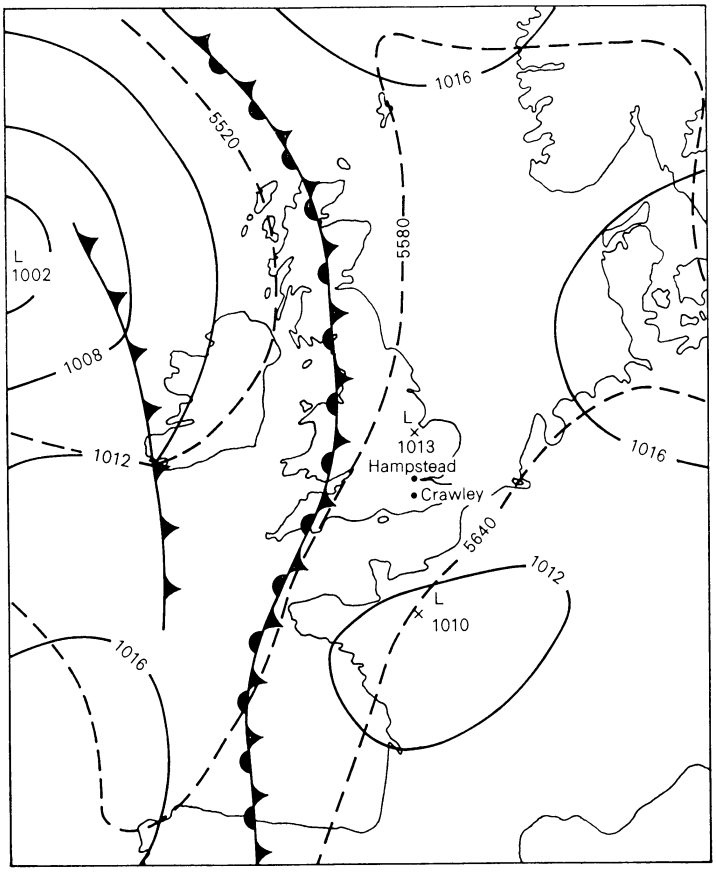

Figure 12. *Synoptic situation over the British Isles at 1200 UTC 14/8/75. (Reproduced from Bailey, Carpenter, Lowther and Passant in Met. Mag. 1981).*

The situation was fairly static with a stationary front over Wales and SW England with very warm air to the east of it. Thunderstorms were thought to be triggered by a combination of the London heat island and the effect of Hampstead hill. Once triggered the storm maintained itself for 3 hours due to the development of new convective cells very close to previously active ones.

A surface chart for a case that was not weakly forced is shown in Figure 13.

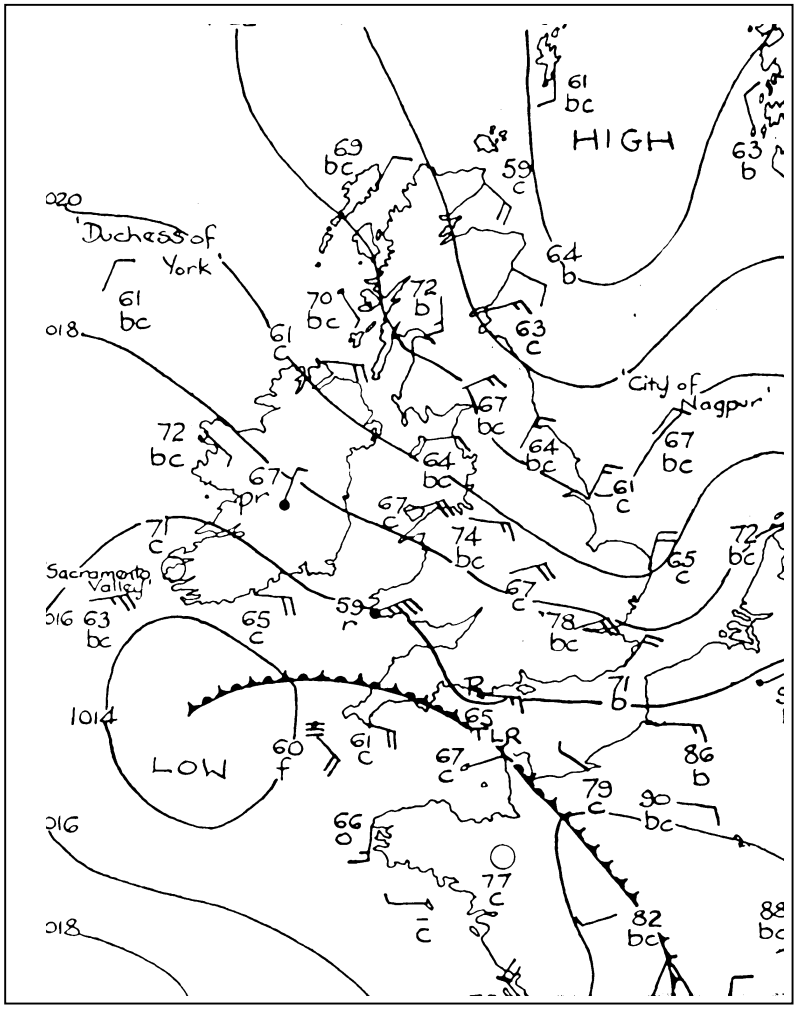

Figure 13. *Surface synoptic chart for 1300 UTC 4/8/38. (Reproduced from Met. Mag. 1938).*

It was very clear that on this occasion the thunderstorms in the Torquay area were triggered by the cold occlusion which had lost most of its frontal precipitation but still remained active as an airmass discontinuity with associated upward air motion.

All of the fronts in the convective cases where the primary triggering mechanism was frontal were of the cold type, ie either a cold front, cold occlusion or trough.

7. Combined analysis of frontal and convective cases

Bringing together the findings in sections 5 and 6 a diagram (see Figure 14) was constructed showing four types of extreme rainfall event.

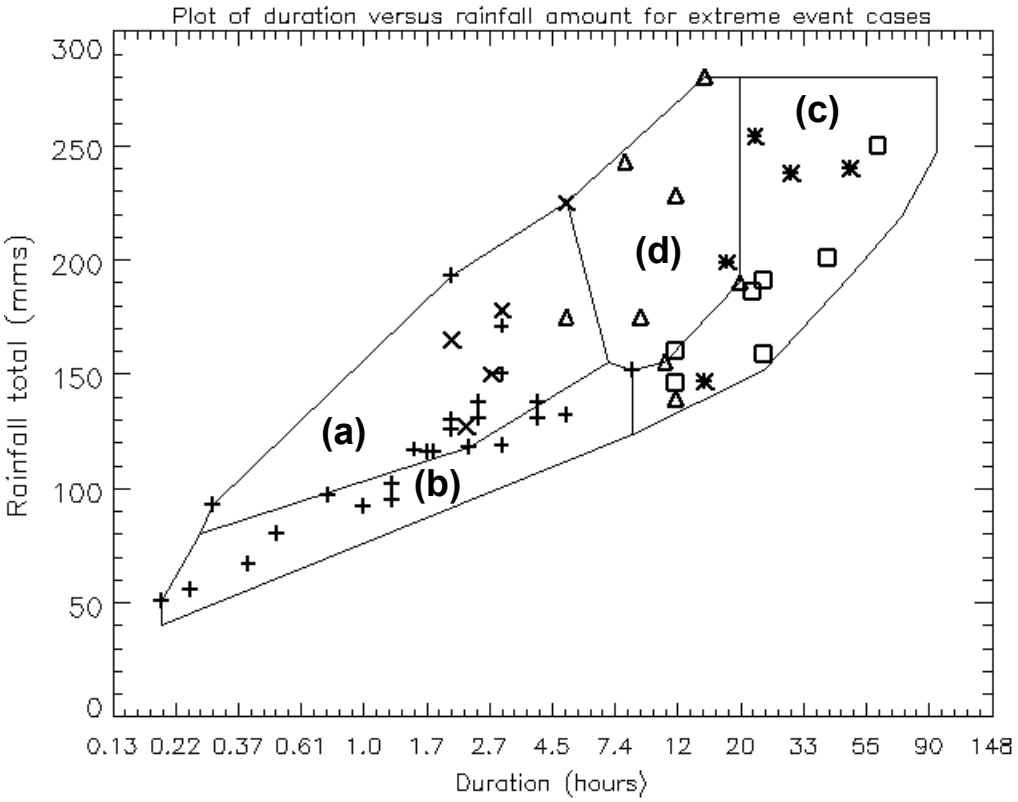

Figure 14. *Diagram showing different regions labelled (a), (b), (c) and (d), which correspond to different types of extreme rainfall event. See text for details. Individual events are marked with '+' = convective , 'X' = convective*** (frontal forcing), * = orographic, Δ = frontal*** (with embedded instability) and 'square' = frontal.*

The types of event in the diagram are as follows:

(a) Severe convective events that are triggered by synoptic scale cold frontal forcing or have large hail. This class also includes isolated near stationary clusters and large multicells in a strongly sheared environment.

(b) Convective events triggered by mesoscale features (e.g. convergence, sea breezes, troughs, upper cold pools, orography or local heating). These events may also have hail but the hail should not be large and damaging or be very prolonged. Some multicellular organisation may also be possible but should not be too self-organizing or long lasting.

(c) Prolonged frontal or orographic events that have little or no convective element.

(d) Frontal (widespread rainfall) events that have a significant convective element (embedded instability).

8. Conclusions

The aim of this work was not to describe a set of case studies but to draw together all the case study evidence into something useful and applicable overall. However, the event references should be useful as a reference for future study and the development of training material for practitioners.

8.1 Conclusions

- Extreme rainfall events are very unlikely to occur in February, March or April.
- Convective events are most likely in June, July, and August and are very unlikely in November, December, January, February, March or April.
- An extreme rainfall event is highly likely to produce serious flooding situations particularly if it occurs over a sensitive catchment or steep orography or when the ground is already very wet from previous rainfalls.
- There was generally a clear distinction between wholly convective and wholly frontal events but with 25% of cases being a mixture of both.
- All frontal cases involved prolonged ascent of very moist air with 75% of cases having a depression pass slowly by within 200 Km at closest approach to the south or east of the event.
- 75% of frontal cases also involved a slow moving front, usually a warm occlusion, in the situation.
- Frontal cases with embedded instability (53%) generally produced larger totals for a given duration and were close to a depression centre.
- An archetypal situation that occurred in several frontal cases is shown below in Figure 15.

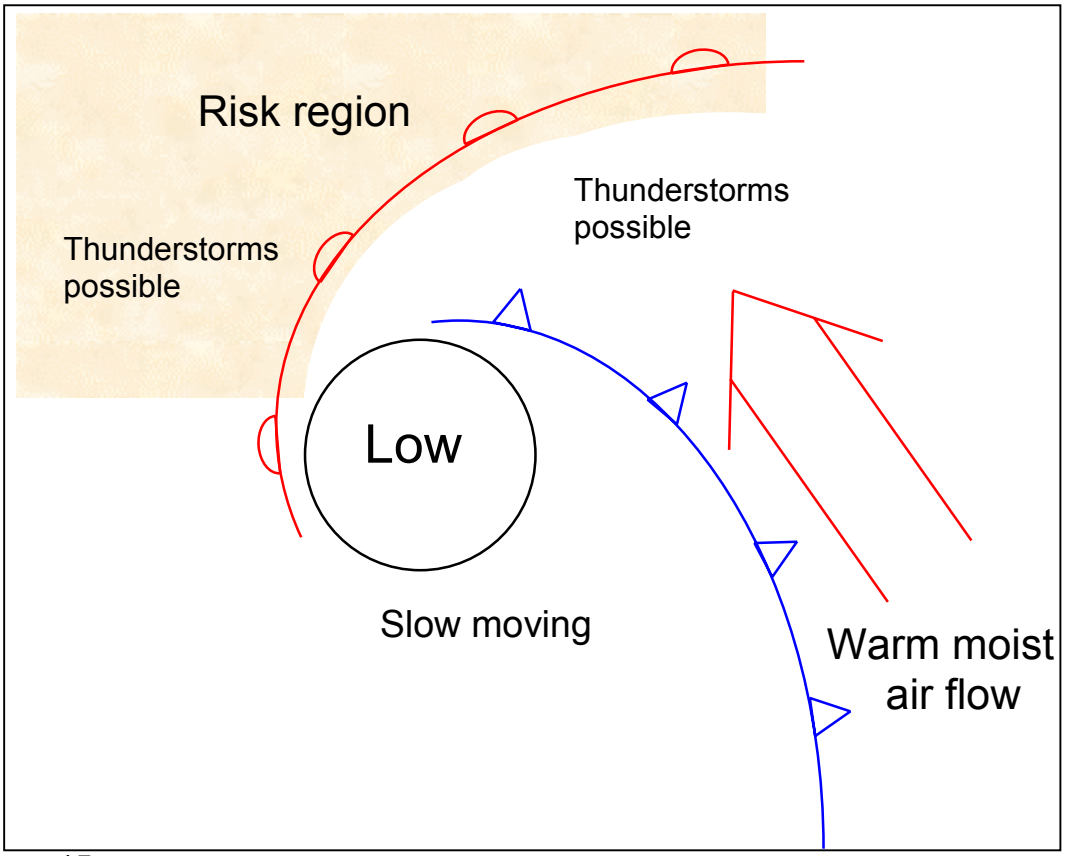

Figure 15. *Schematic diagram showing archetypal situation that occurred in several of the extreme frontal events. The main region at risk of extreme rainfall is shaded. Cold front is shown with blue 'spikes' and warm front with red 'bobbles'. The direction of the main warm and moist airflow is shown by the broad red arrow. (See text for interpretation).*

The schematic illustrates the main features that occurred in 10 out of 15 of the frontal cases; 21/10/08, 26/08/12, 22/07/30, 15/07/37, 12/08/48, 15/08/52, 10/07/68, 15/09/68, 20/09/73 and 31/08/94. Although details and orientations were different the key similarities were a slow moving low within 200 Km of the event, a warm moist ascending airflow marked by a slow moving warm front or occlusion, the possibility of instability release leading to thunderstorms either close to the low centre or within the ascending warm airmass, the extreme rainfall either along the warm front (occlusion) or in the northwest quadrant relative to the low centre.

- All orographic events occurred in either December, January or February and were associated with a high pressure region over the Bay of Biscay or Spain with a very strong west to southwest flow with a fetch greater than 2000 Km persisting for 15 hours or more. The dewpoint of the air in the source region was estimated to be greater than 14 deg C and the average geostrophic (600m) wind along the fetch was greater than 15 m/s.

- Convective events were either weakly forced (potentially unstable) or associated with large synoptic features such as a cold front or occlusion. The presence of large hail was very useful for discriminating the more severe events.

- All events can be categorized into four basic types, (five if orographic events are considered separately), which could form the basis of future work in devising methods for formulating 24 hour early warnings of extreme rainfall.

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